Room Temperature Bubble Point Tests on Porous Screens: Implications for Cryogenic Liquid Acquisition Devices

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Abstract

We present experimental results for room temperature bubble point tests conducted at the Cedar Creek Road Cryogenic Complex, Cell 7 (CCL-7) at the NASA Glenn Research Center. The purpose of these tests was to investigate the performance of three different fine mesh screens in room temperature liquids to provide pretest predictions in cryogenic liquid nitrogen (LN_2) and hydrogen (LH_2) as part of NASA's microgravity LAD technology development program. Bench type tests based on the maximum bubble point method were conducted for a 325x2300, 450x2750, and 510x3600 mesh sample in pure room temperature liquid methanol, acetone, isopropyl alcohol, water, and mixtures of methanol and water to cover the intermediate to upper surface tension range.

A theoretical model for the bubble point pressure is derived from the Young-LaPlace equation for the pressure drop across a curved interface. Governing equations are reduced in complexity through a set of simplifying assumptions to permit direct comparison with the experimental data. Screen pore sizes are estimated from scanning electron microscopy (SEM) to make pretest predictions. Pore sizes based on SEM analysis are compared with historical data available in the literature for the 325x2300 and 450x2750 screens as well with data obtained from bubble point tests conducted in this work.

Experimental results show that bubble point pressure is proportional to the surface tension of the liquid. We show that there is excellent agreement between data and model for pure fluids when the data is corrected for non-zero contact angle measured on the screens using a modified Sessile Drop technique.

SEM image analysis of the three meshes indicated that bubble point pressure would be a maximum for the finest mesh screen. The pore diameters based on SEM analysis and experimental data obtained here are in excellent agreement for the 325x2300 and 450x2750 meshes, but not for the finest 510x3600 mesh. Therefore the simplified model can be used to interpolate predictions for low surface tension cryogenic liquids only when pore diameters are based on room temperature bubble point tests and not SEM analysis as presently implemented.

Outline

Background
- PMD Overview
- Test Purpose

Theoretical Model
- Assumptions
- Governing Equations

Test Description
- Experimental Design
- Experimental Procedure

Results
- SEM Pore Diameter Measurements
- Contact Angle Measurements
- Predictions
- Bubble Point Tests

Conclusions and Predictions for Liquid Hydrogen

Background

PMD Overview – Fundamental Fluid Physics

Subsystem requirement - transfer single phase propellant from a tank to the transfer line en route to an engine or receiver tank

Separation of liquid and vapor phases governed by lowest achievable potential energy state

1-g Fluid transfer

- Gravitational force is the driver
- Liquid → bottom, vapor → top

Single phase flow strategy:

- Settling thrusting maneuvers
- Anti-vortex baffle and/or mesh
- Tank exit valve

0-g fluid transfer

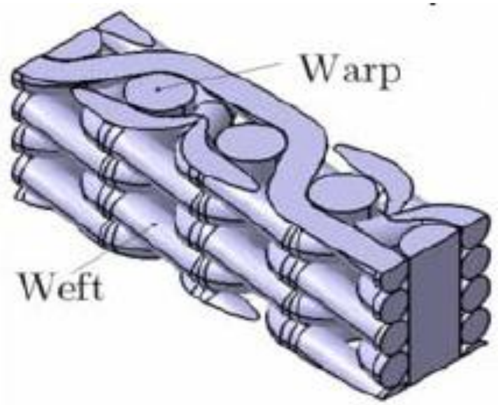
- Surface tension force is the driver
- Liquid → outer walls , vapor → center

Single phase flow strategy:

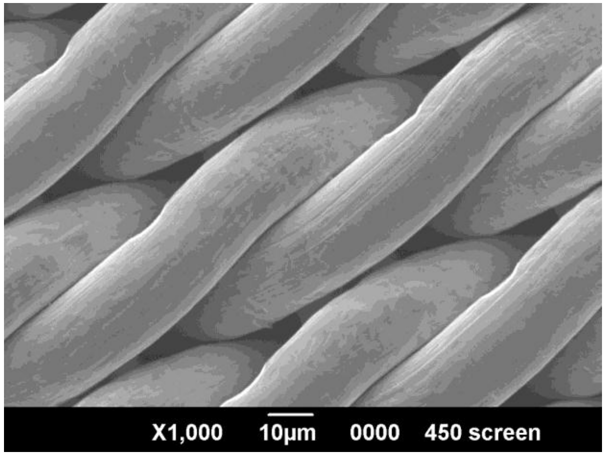
- Full "communication" device – usually a fine mesh or vane alongside tank wall
- Rely on capillary flow, wicking, micron sized pores
- Exit sump
- Tank exit valve

PMD Overview – Screen Channel Liquid Acquisition Devices

- Screen channel gallery arms are best in multi-directional, multi-g environments
- Multiple screen mesh styles – square, Dutch Twill (tortuous flow path)
- Warp/shute wires characterize the mesh (ex. 325x2300)
- LADs rely on wicking, capillary flow, surface tension for barrier to vapor ingestion
- No optimized LAD configuration; fine mesh screens = good wicking & screen retention vs. high pressure drop and potential for clogging
- Smaller pore sizes (< 20 μm) are favorable for low surface tension fluid acquisition



Credit: Conrath, M. and Dreyer, M. (2009)



Purpose

1. Develop a simplified bubble point pressure model
2. Collect bubble point data in 4 fluids using 3 new fine mesh LAD screen samples and compare data to model
3. Make pretest predictions for future LH_2 tests

Theoretical Model for ΔP_{BP}

The Bubble Point

- Screens fail when vapor is ingested across the channel
- Definition: differential pressure across a screen pore that overcomes the surface tension of the liquid at that pore
- Measurable quantity
- Primary performance parameter
- ΔP_{BP} is upper limit on total allowable pressure loss for a LAD system

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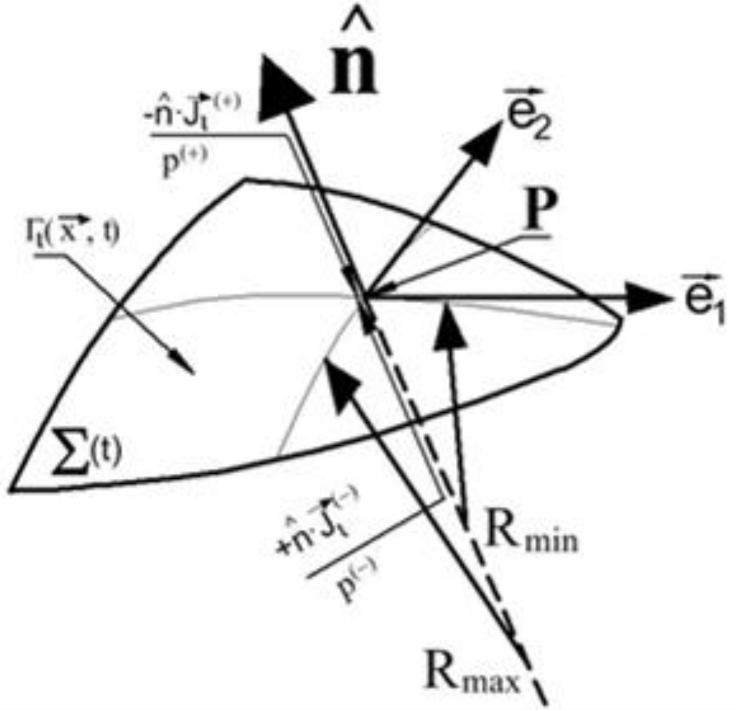
The Bubble Point

- Consider the surface formed by a general liquid/vapor interface:

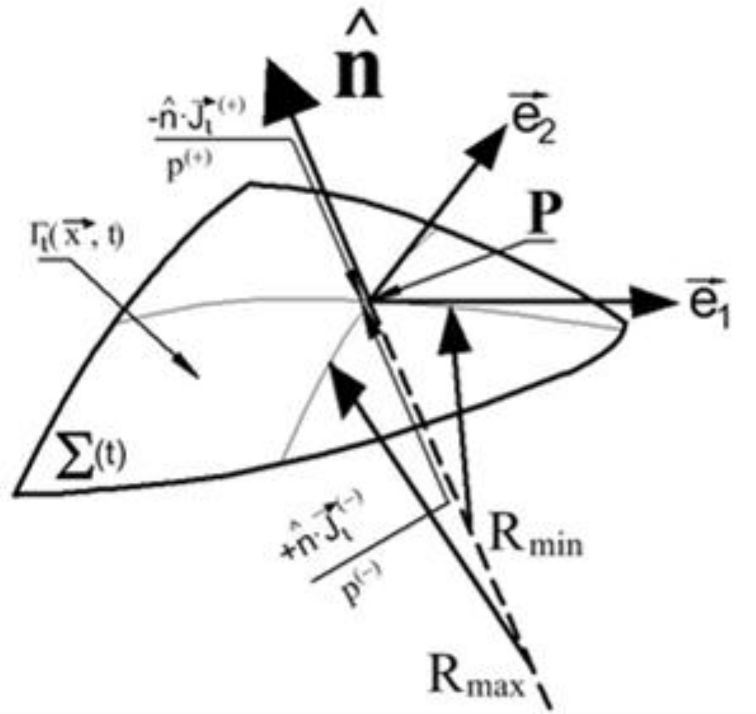
- Principle radii of curvature: $R_{\min,} R_{\max}$
- Adsorbing or desorbing from surface: $\pm n \cdot J_i$
- Surface excess: $\Gamma_i(\vec{x}, t)$



Liquid on top,
vapor on bottom

The Bubble Point

- Consider the surface formed by a general liquid/vapor interface:



- Principle radii of curvature: $R_{\min,} R_{\max}$

#1 Neglect reactions, diffusions, adsorption/desorption

Young-LaPlace equation: $[P] = \gamma_{LV} \nabla \cdot n$

- Surface free energy: γ_{LV}

- Divergence of unit normal related to mean curvature: $2H \overset{def}{=} \nabla \cdot n$

#2 L/V interface is zero thickness

Liquid on top, vapor on bottom

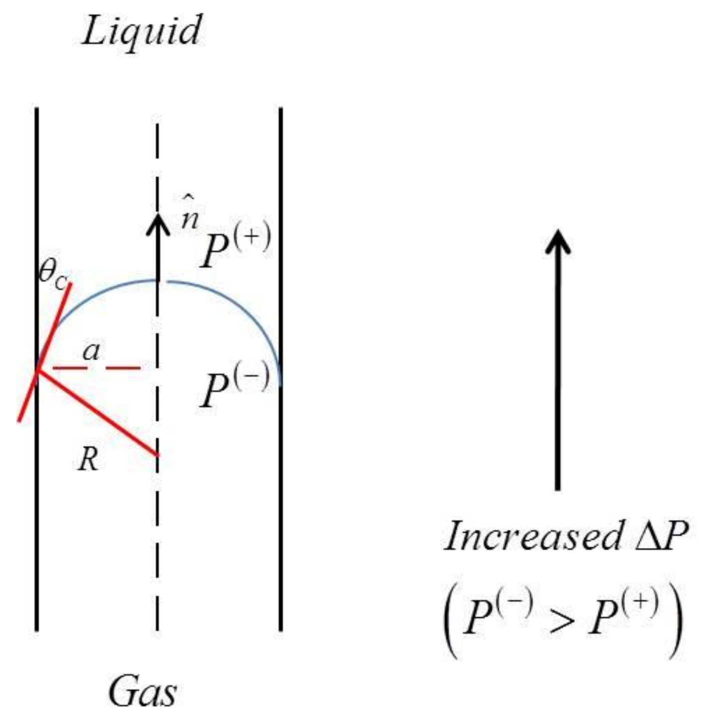
The Bubble Point

Young-LaPlace equation: $\Delta P = 2\gamma_{LV} H$

- Mean curvature rewritten as $2H = \left(\frac{1}{R_{\min}} + \frac{1}{R_{\max}} \right)$

#3 Screen pore = vertical capillary tube

- Now, $R = a\cos\theta_C$ where a is tube radius
  $\cos\theta_C$ is advancing contact angle



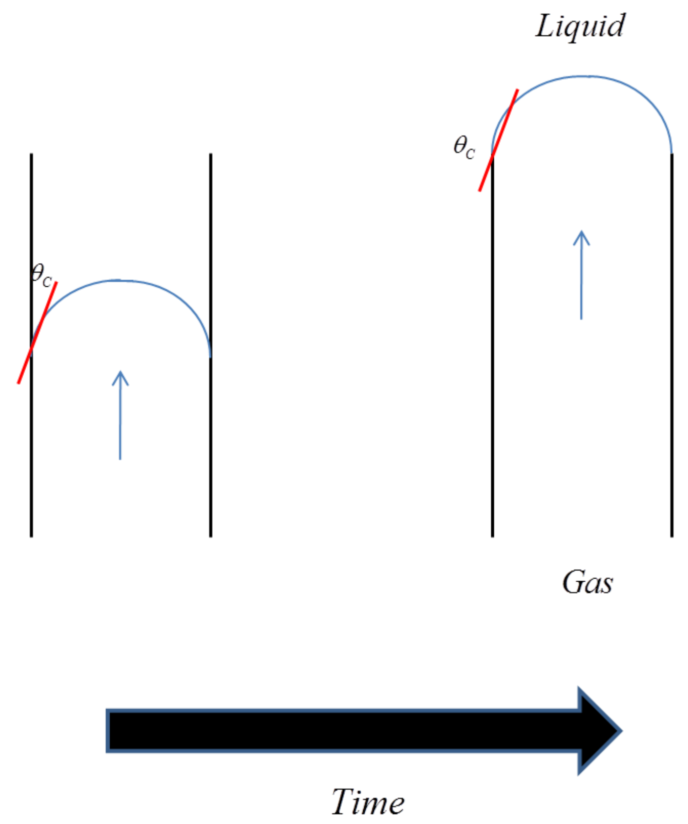
#4 Approximate the L/V interface as 2D interface

i.e. can use hydraulic diameter

- Relates ideal capillary tube to actual complex screen pore structure $a = \frac{D_P}{2}$

The Bubble Point

Young-LaPlace equation: $\Delta P = \dfrac{4\gamma_{LV}\cos\theta_C}{D_P}$



To permit relation to the measured bubble point and contact angle:

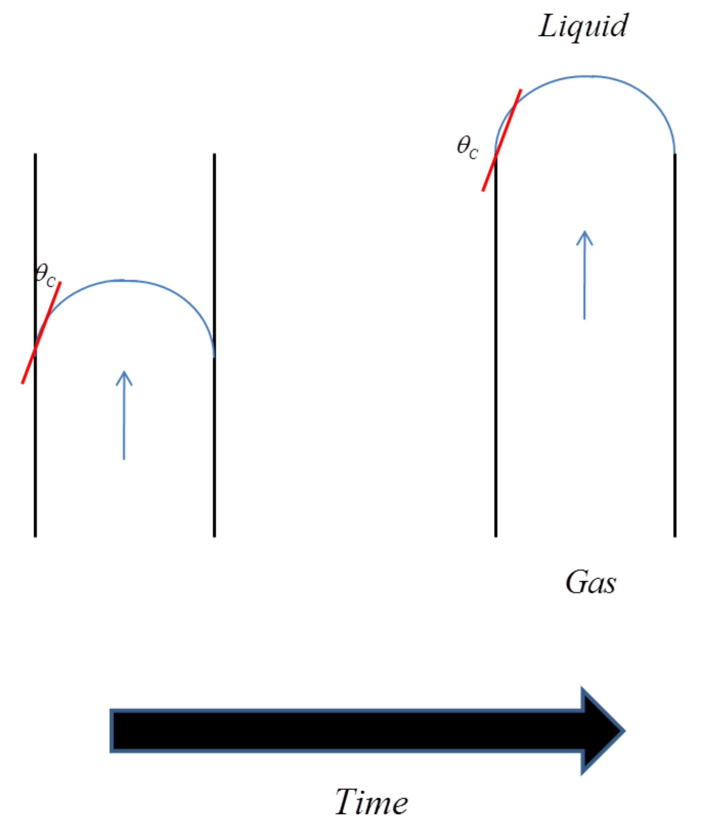
#5 Pressurization done in fixed quasi-static steps

#6 θ_C at pore throat = θ_C at pore mouth

#7 Microscopic θ_C at pore mouth = Macroscopic θ_C on screen

$$\boxed{\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}}$$

The Bubble Point



Previous experiments

Measured

Measured

$$\boxed{\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}}$$

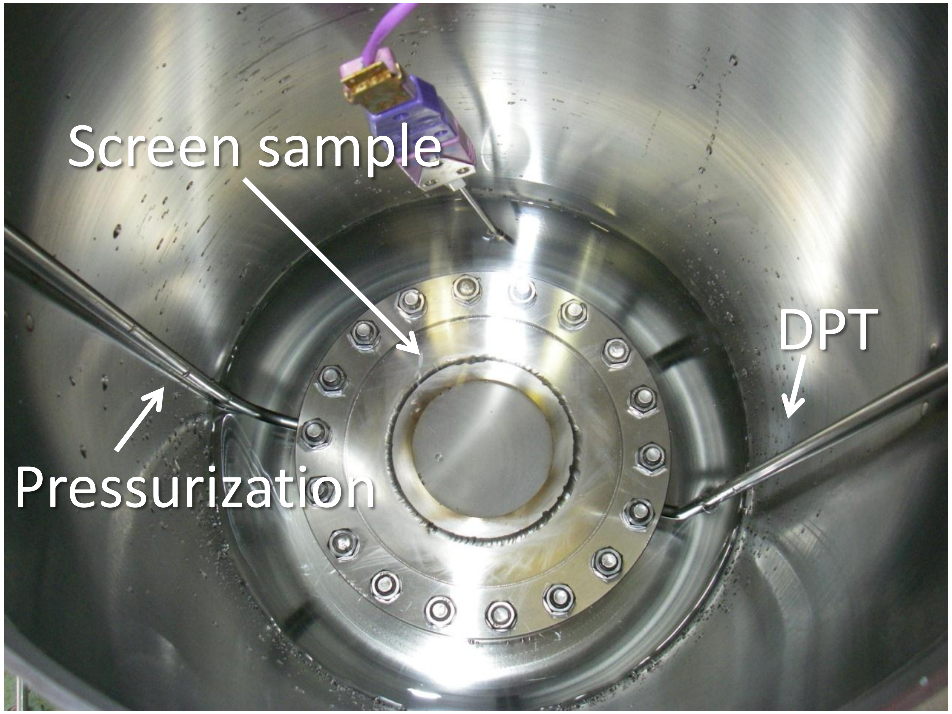
Determined by either:

1. Similitude using reference fluid bubble point tests
2. Historical reference (where available)
3. SEM Analysis

Test Description

Experimental Design

- Three 6.5 cm OD LAD screen samples (325x2300, 450x2750, 510x3600)
- Helium pressurization gas
- High surface tension liquids (relative to cryogenic): acetone, IPA, methanol, water



- Screens welded to flange w/ ports
- Inverted configuration
- Purpose of the flange is to create L/V interface by pressurizing underside of screen

Measurements

T: L (1)

P: DPT across screen 0-3 psid (0 – 20 kPa) Labview DAQ

Height: ruler

Visualization: camera with time synch

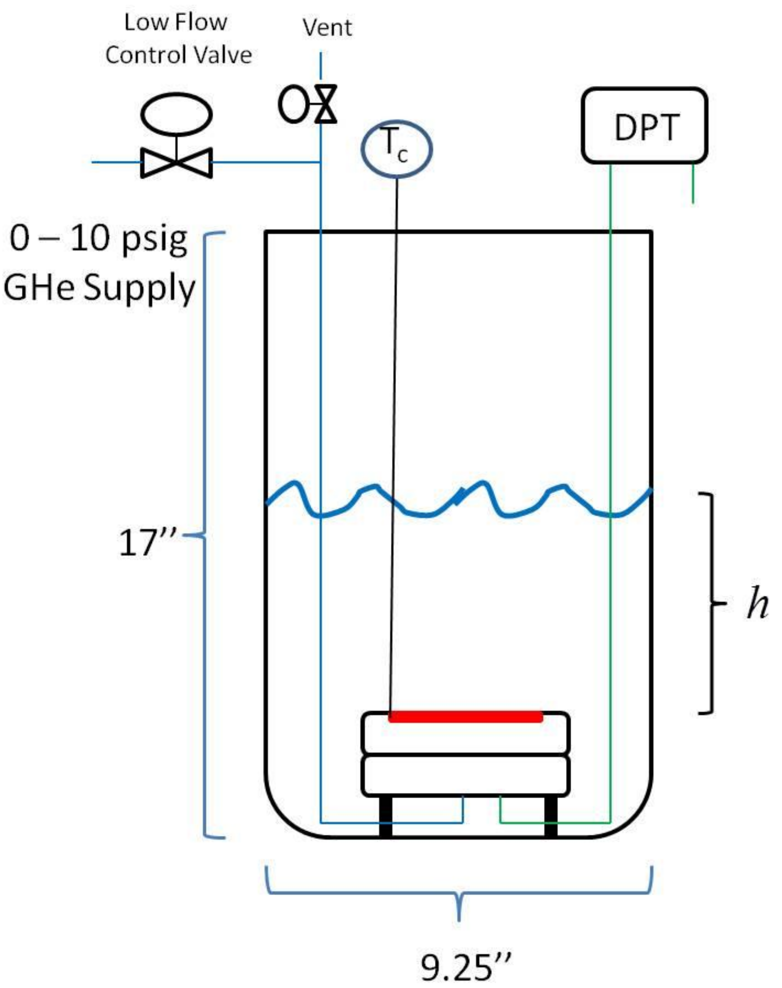
Experimental Design

- Screen/flange mounted inside vertical cylinder
- Purpose of cylinder was to house reference liquids on top of screen
- 0-10 psig Ghe supply regulated by low flow control valve for slowest possible ramp rate
- Vent line to relieve pressure between tests
- Measured bubble point pressure:

$$\Delta P_{BP} = \Delta P_{DPT} - \rho_{liquid}\left(T\right)gh$$

Uncertainty

- Temperature (+/- 1K)
- DPT (+/- 62.0 Pa)
- Height (+/- 3.2 mm)
- Bubble Point: (+/- 62.3 Pa) < 1.2% at lowest measured value



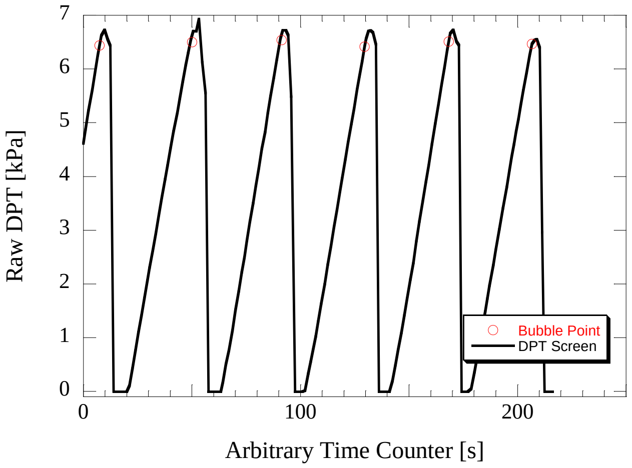
Experimental Procedure

Prior to Bubble Point Tests

- Dry helium purge of vertical cylinder, flange, pressurization and sense lines
- Establish GHe flow across screen
- Fill vertical holding cylinder with desired reference liquid

Bubble Point Tests

- Slowly increase pressure underneath screen until breakdown
- Note the time at breakthrough, correlate with the data file
- Reseal the screen, vent off pressure, repeat



After Bubble Point Tests

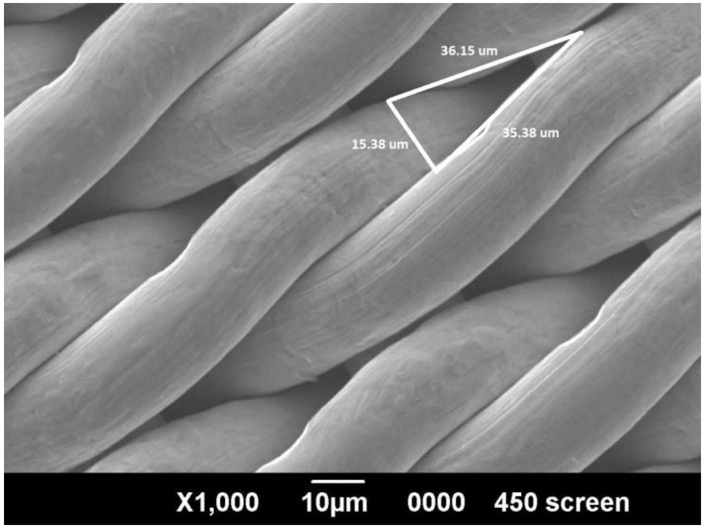
- Remove liquid from vertical cylinder
- Purge all lines and screens with dry helium
- Chemically clean screens 2-3 times in acetone bath + warm ambient drying
- Repeat with next reference liquid

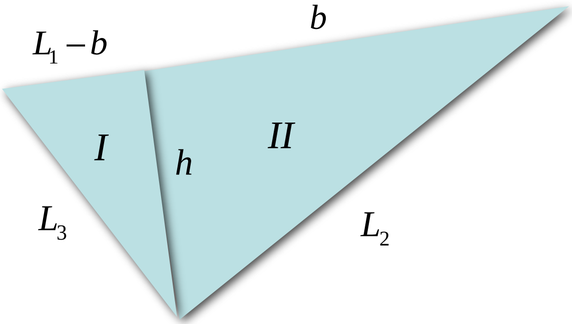
Results

Scanning Electron Microscopy (SEM) Imaging

- Cannot use (method 2) historical reference for all three screens
    - Only sparse data for 450x2750 screen; no previously reported 510x3600 data
- Estimate 2D planar triangular pore diameter from SEM analysis (method 3)

3 test samples (1 per screen) were imaged :





$$b = \frac{1}{2L_1}\left(L_1^2 + L_2^2 - L_3^2\right)$$

$$h = \sqrt{\left(L_2^2 - b^2\right)}$$

$$D_{P,SEM} = \frac{4A_c}{P}$$

$$D_{P,SEM} = \frac{4\left(A_I + A_{II}\right)}{\left(L_1 + L_2 + L_3\right)}$$

	Screen Characteristics				Pore Diameter [µm]
Mesh	n warp	n shute	d warp [µm]	d shute [µm]	Based on SEM
325x2300	325	2300	38.1	25.4	14.8 ± 0.05
450x2750	450	2750	25.4	20.3	11.9 ± 0.05
510x3600	510	3600	25.4	15.2	9.95 ± 0.05

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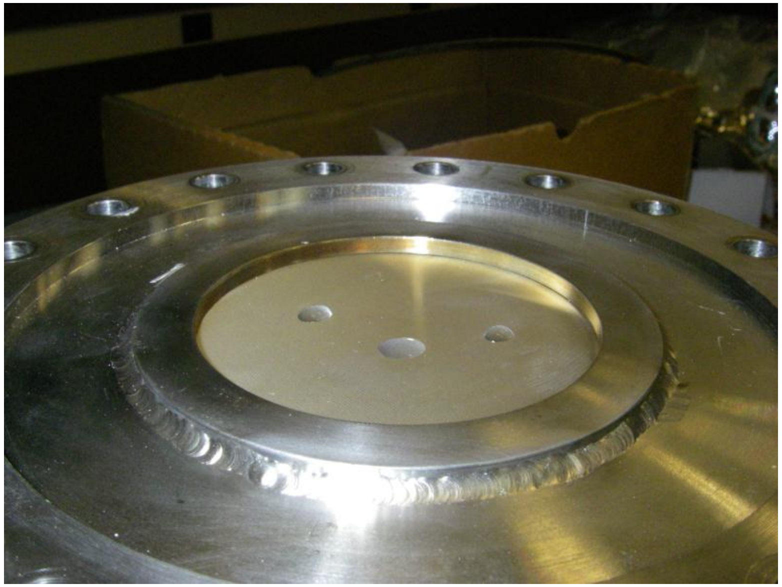
Advancing Contact Angle Measurements

- Contact angle previously assumed zero for all previously reported bubble points

- Modified version of Sessile Drop method
  - measure R_{drop} (t) with camera and ruler
    R_{drop} (t) with syringe

- θ_c deduced from inner angle of oblate sphere



Water droplets on a 510x3600 sample

Fluid	Contact Angle [deg]	BP Correction Factor (Cos Theta)
Water	49.5 ± 1	0.649
IPA	6.3 ± 1	0.994
Methanol	5.4 ± 1	0.996
Acetone	5.97 ± 1	0.995

Note: Porous 304SS screen contact angles slightly less than solid SS

Theoretical Predictions

$$\gamma_{LV} = A*(1-T_R)^{\left(B+C*T_R+D*T_R^2\right)} \quad \left[{}^{mN}\!/_{m}\right]$$

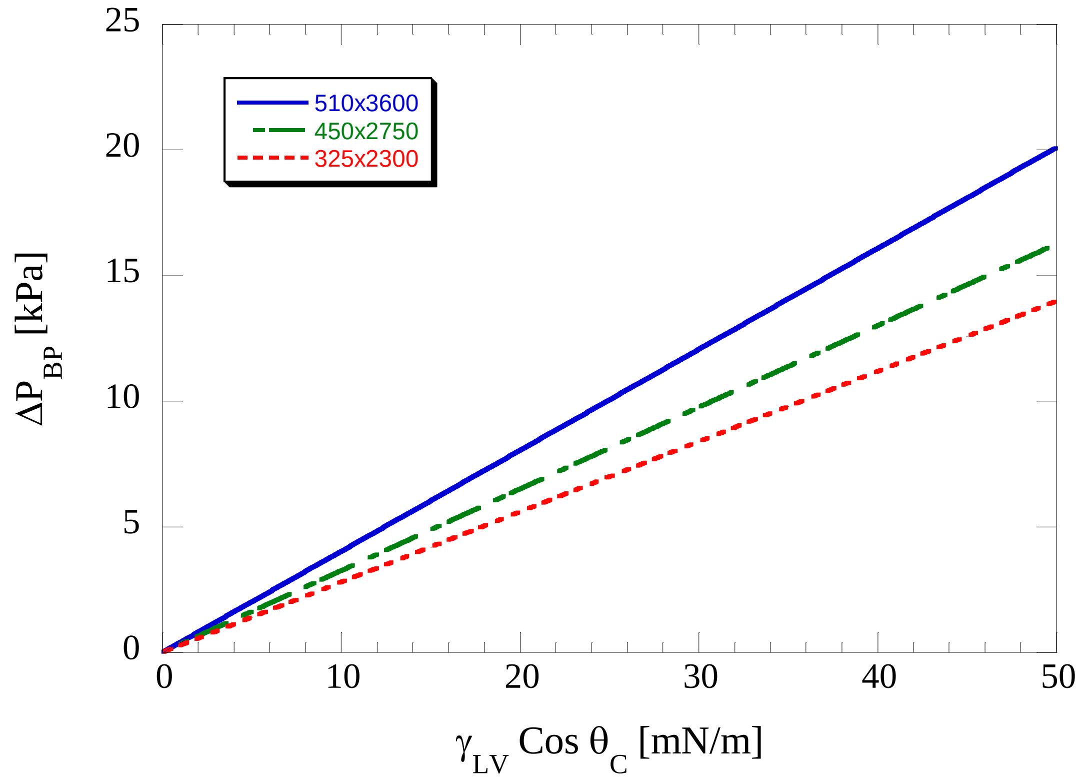
- Temperature dependent surface tension obtained from databases & literature:

	Methanol	Acetone	IPA	Water
Tmin [K]	175	182	287	233
Tmax [K]	508	329	353	643
Tcritical [K]	512.16	508.1	508.3	647
A	102.06	63.442	46.507	134.15
B	4.2709	1.1612	0.90053	1.6146
C	-6.0509	0	0	-2.035
D	2.9715	0	0	1.5598

- Using pore diameters based on SEM:

$$\Delta P \propto \gamma_{LV} \cos\theta_C$$

$$\Delta P \propto \frac{1}{D_{P,SEM}}$$



Room Temperature Bubble Point Tests

Bubble Point Liquid Dependence

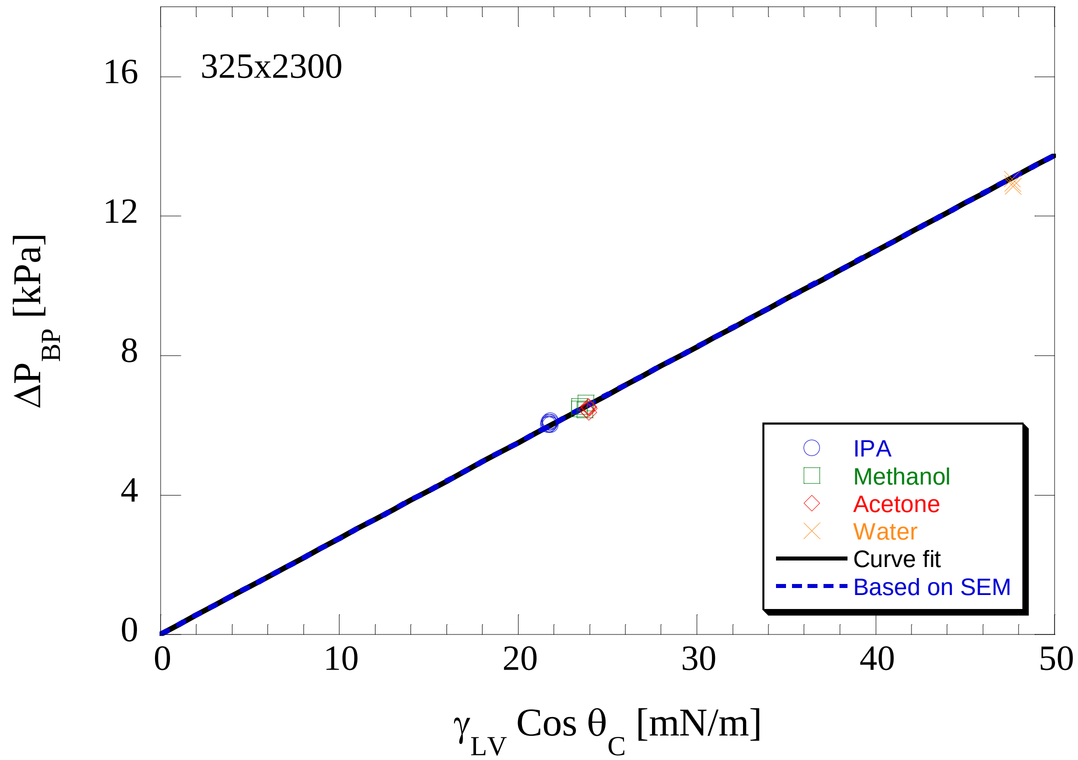
- For 325x2300,

$$D_{P,Similitude} = D_{P,SEM}$$

- For 325x2300:

$$\Delta P \propto \gamma_{LV} \cos\theta_C$$

$$\Delta P \propto \frac{1}{D_{P,SEM}}$$

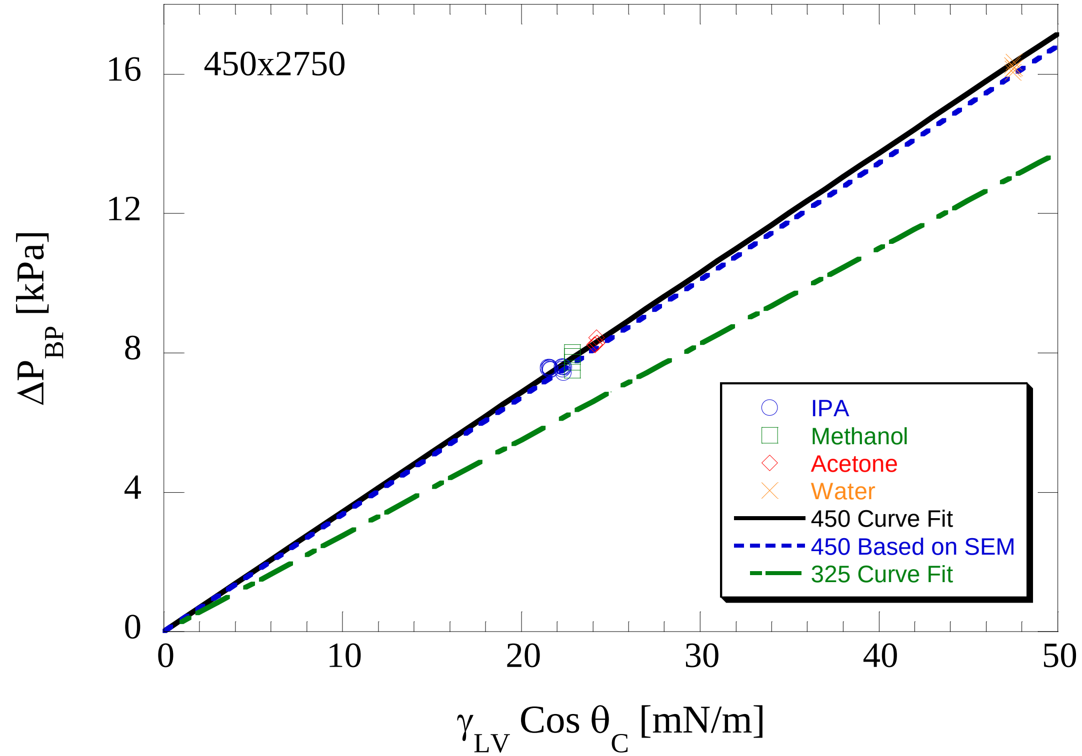


Room Temperature Bubble Point Tests

Bubble Point Liquid Dependence

- For 325x2300, 450x2750

$$D_{P,Similitude} = D_{P,SEM}$$



- For 325x2300, 450x2750:

$$\Delta P \propto \gamma_{LV} \cos\theta_C$$

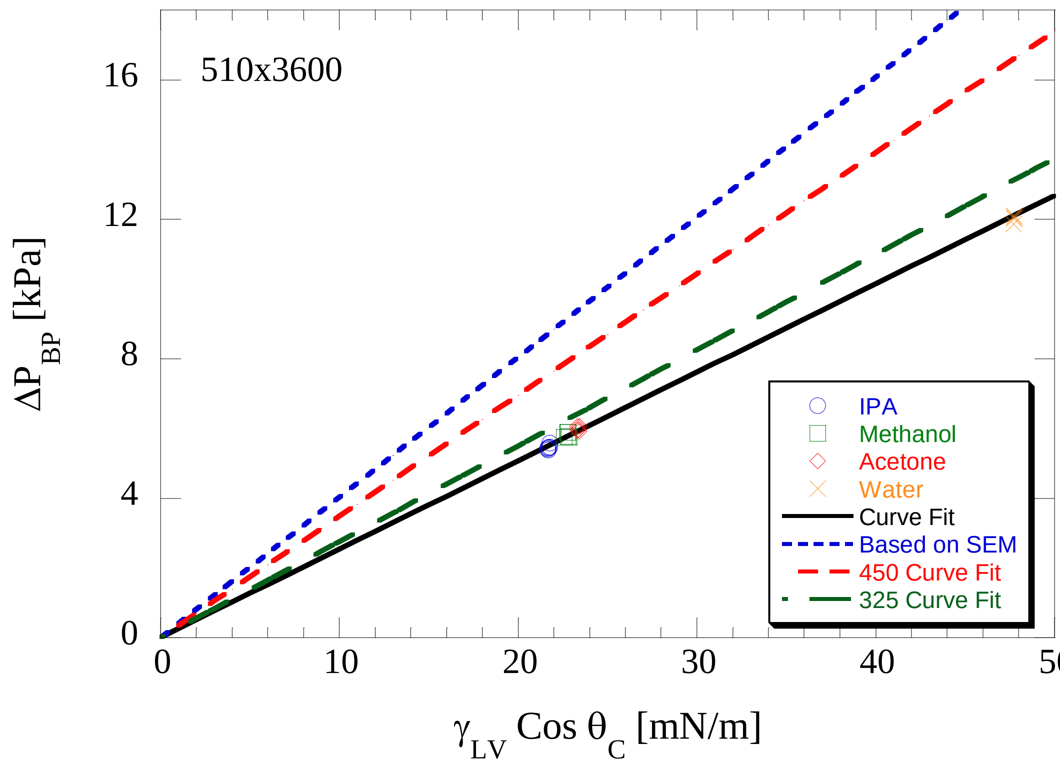
$$\Delta P \propto \frac{1}{D_{P,SEM}}$$

Room Temperature Bubble Point Tests

Bubble Point Screen Weave Dependence

- For 510x3600

$$D_{P,Similitude} \neq D_{P,SEM}$$



- For 325x2300, 450x2750, 510x3600:

$$\Delta P \propto \gamma_{LV} \cos\theta_C$$

$$\Delta P \propto \frac{1}{D_{P,SEM}}$$

Room Temperature Bubble Point Tests

Bubble Point Screen Weave Dependence

- 325x2300 and 450x2750 both outperform 510x3600!
- Good agreement with historical data
- Discrepancy may be attributed to fact that SEM pore diameters based on 2D projection on plane; actual L/V is embedded within screen

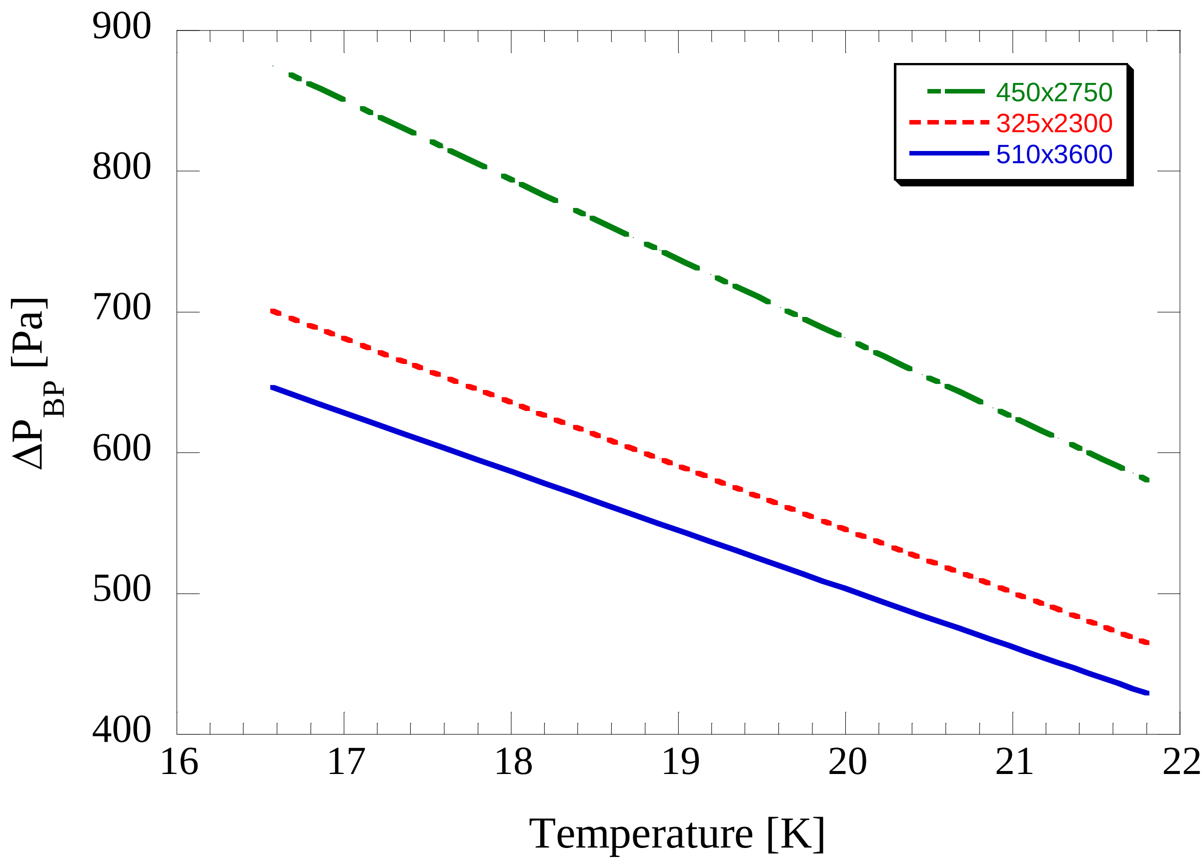
	Pore Diameter [μm]		
	Method 1	**Method 2**	**Method 3**
	Current Work	**Historical**	**Based on SEM**
325x2300	14.55 ± 0.3225	14.6 ± 0.55	14.8 ± 0.05
450x2750	11.65 ± 0.3225	11.8 ± 0.55	11.9 ± 0.05
510x3600	15.77 ± 0.3225	-	9.95 ± 0.05

$$\Delta P \propto \gamma_{LV} \cos\theta_C$$ ✓

$$\Delta P \propto \frac{1}{D_{P,Similitude}}$$ ✓

Liquid Hydrogen Pretest Predictions

- **Temps representative of a low pressure cryo flight propellant tank**
- **Curves based on** $D_{P,Similitude}$



- **450x2750: 25% margin over the baseline 325x2300 screen**
- **Excess margin in bubble point translates into more margin in total allowable flow rate to engine**

Conclusion

1. Simplified bubble point model works well when effective pore diameters are based on reference fluid tests, not SEM analysis.
2. Bubble point pressure is proportional to contact angle corrected liquid surface tension for acetone, IPA, methanol, water for all three meshes.
3. Bubble point values qualitatively scale with the mesh of the screen for 325x2300 and 450x2750 screens, but not the 510x3600 screen.

4. Results suggest geometrical effects of L/V interface impact D_p.
5. Results hint at existence of an optimal screen weave.
6. Results indicate 450 buys > 25% margin over 325 for LH2 (has to be confirmed).

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